

Computational Analyses in Support of Sub-scale Diffuser Testing for the A-3 Facility – Part 3: Aero-Acoustic Analyses and Experimental Validation

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A unique assessment of acoustic similarity scaling laws and acoustic analogy methodologies in predicting the far-field acoustic signature from a sub-scale altitude rocket test facility at the NASA Stennis Space Center was performed. A directional, point-source similarity analysis was implemented for predicting the acoustic far-field. In this approach, experimental acoustic data obtained from “similar” rocket engine tests were appropriately scaled using key geometric and dynamic parameters. The accuracy of this engineering-level method is discussed by comparing the predictions with acoustic far-field measurements obtained. In addition, a CFD solver was coupled with a Lilley’s acoustic analogy formulation to determine the improvement of using a physics-based methodology over an experimental correlation approach. In the current work, steady-state Reynolds-averaged Navier-Stokes calculations were used to model the internal flow of the rocket engine and altitude diffuser. These internal flow simulations provided the necessary realistic input conditions for external plume simulations. The CFD plume simulations were then used to provide the spatial turbulent noise source distributions in the acoustic analogy calculations. Preliminary findings of these studies will be discussed.

Nomenclature

D	=	exit diameter of subscale altitude facility
f	=	frequency
OASPL	=	overall sound pressure level
r	=	radial distance from facility exit
St	=	Strouhal Number
U	=	exit velocity

I. Introduction

A. The Constellation Program

The Constellation Program is NASA’s new endeavor to broaden its manned space exploration efforts by returning back to the Moon. The mission durations on the lunar surface will be for much longer periods of time than that which were conducted during the Apollo Program. One of the primary objectives of this new exploration effort will be to develop both the experience and technology necessary for accomplishing future manned expeditions to Mars and beyond.

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Two new transport vehicles, ARES V and ARES I, have been proposed to support the Constellation Program efforts^{1, 2}. Figure 1 shows a conceptual structure of the ARES vehicles. The core-stage of the ARES V vehicle has an external casing diameter of 33 ft and will be powered either by five or six Pratt & Whitney Rocketdyne RS-68 LOX/LH₂ engines³. The RS-68 engine is currently being used as the powerplant for the Delta IV expendable launch vehicle, and undergoing certification testing at the NASA Stennis Space Center, as shown in Figure 2a.

The Earth departure stage (EDS) of ARES V and the upper stage of ARES I (diameter of 18 ft) will both be powered by single J-2X engines. The J-2X engine, also to be manufactured by Pratt & Whitney Rocketdyne, is not currently under production. It will consist of a blend of the Apollo-era J-2 engine that powered the 2nd and 3rd stage of the Saturn V, and the streamlined J-2S engine which was developed and tested in the late 1970's but never flew. A conceptual rendering of the J-2X is depicted in Figure 2b. The planned engine specifications for the new ARES power plants are summarized in Table 1⁴⁻⁷.

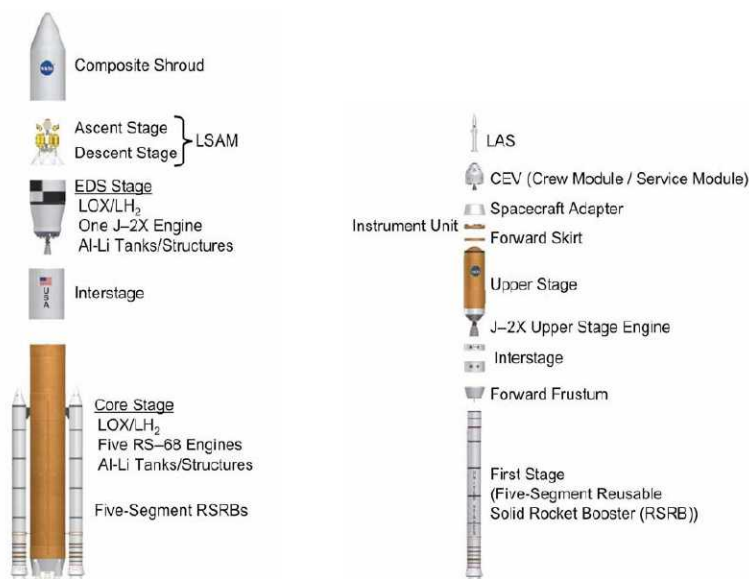


Figure 1: ARES V (left) and ARES I (right) Vehicles^{1, 2}

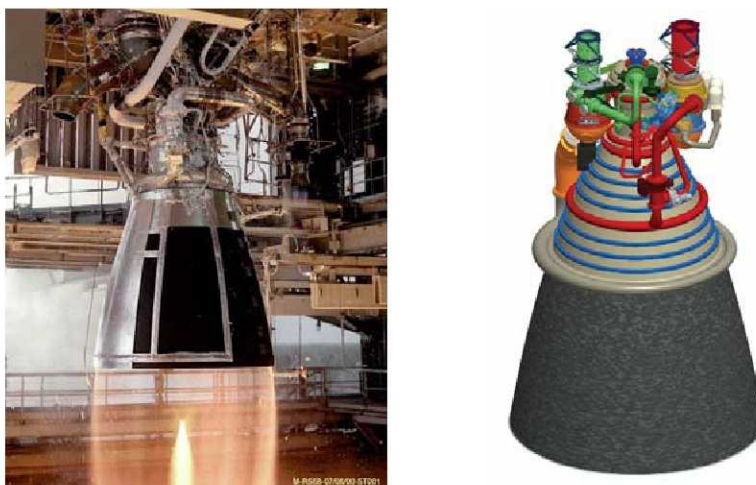


Figure 2: An RS-68 Engine Test at the NASA Stennis Space Center B-1 Test Facility and a Conceptual Rendering of the J-2X Engine^{1, 2}

Table 1: Conceptual RS-68 and J-2X Engine Specifications

	<i>RS-68^{4,5}</i>	<i>J-2X^{6,7}</i>
Engine Cycle	Gas Generator	Gas Generator
Propellants	LOX/LH ₂	LOX/LH ₂
Mixture Ratio	6.0	5.5
Chamber Pressure (psia)	1450	1338
Thrust (K-lbf)	758 (v) / 663 (sl)	294 (v)
Isp (sec)	409 (v) / 357 (sl)	448 (v)
Expansion Area Ratio	21.5	-
Exit Diameter (in)	96	-

B. The NASA Stennis A-3 and A-3 Subscale Test Facilities

The NASA John C. Stennis Space Center (NASA-SSC) has been selected as the rocket propulsion test center responsible for testing and certification of the J-2X upper stage engine at altitude conditions. The test requirements are that the engine must be tested at start conditions of 100,000 ft (or 0.16psia) simulated altitude. To meet these requirements, a new altitude test stand (A-3) has been designed and is currently being constructed. The A-3 altitude test stand, depicted in Figure 3, is a very unique facility. It is a vertical test stand of steel structure with a two-stage steam ejector pumping system. An array of 27 chemical steam generators provide the driving medium for the ejector aerodynamic pumping, and at nominal design conditions should effectively pump the test cell down to 0.16 psia prior to engine start.

Due to the mission-criticality of having a reliable and successful A-3 facility, a sub-scale test facility was built and tested at the NASA-SSC E-Complex. This test program was a risk mitigation effort to verify engineering predictions upon which a multi-million dollar material procurement are based, provide test operation experience with the unique diffuser-ejector train design of A-3, and pinpoint any potential design flaws prior to construction of the full-scale A-3 facility. The A-3 sub-scale diffuser is 1/17th geometric scale of the full-scale diffuser. The sub-scale version of the J-2X engine, or J2 Sub-Scale (JSS), consists of a 1,000 lbf rocket engine with a modified chamber liner, throat, and nozzle that are 1/17th scale of the J-2X.

Due to the placement of the new A-3 facility and its proximity to populated areas and frequently traveled highways, it is imperative to have a complete understanding of the expected far-field acoustic signature from the A-3 test facility. However, the majority of available rocket testing acoustic data are not for test facilities of this type. Furthermore, the available rocket acoustic modeling tools have not be validated for the heavily steam-laded and relatively slower A-3 exhaust plume. Thus, to support of the A-3 test program, aero-acoustic analyses has been performed in conjunction with far-field acoustic data collection of the sub-scale facility during its nominal operation. The primary objective in conducting this study was to develop a validated methodology for characterising the farfield acoustic signature from an altitude rocket test facility of this type. Also, as a result of this sub-scale analysis effort, the lessons and insights gained would provide a higher confidence level in the acoustic analyses being conducted on the A-3 full-scale facility.

II. Predictive Methodologies

A complete in-depth description of the acoustic scaling methodology and the combined CFD/acoustic analogy methodology implemented in the current work will be added in the final manuscript.

III. Experimental Facility

A. Subscale Altitude Test Facility

To help minimize risk of failure and cost of the new A-3 altitude test facility at NASA Stennis Space Center, a subscale altitude facility was designed and constructed to perform a series of verification tests. These verification tests could potentially pinpoint design and/or operational issues with the A-3 test stand prior to its construction. The subscale test facility, shown in Figure 3, is approximately 1/17th scale of the A-3 test facility. A subscale J-2X engine has also been constructed and installed in the test facility. The area ratios, combustion chamber pressure and mixture fractions of the J-2X have been maintained in the subscale engine. As a result, the subscale engine plume entering the diffuser closely resembles that of the J-2X. The mass flow rates of the 1st and 2nd steam ejectors have also been appropriately scaled to ensure the same gas dynamic processes are occurring inside the subscale diffuser flow path. The subscale diffuser has been instrumented with an array of high-speed pressure transducers and thermal couples to assess the facility operation behavior and efficiency. The high-speed diffuser data in conjunction with IR outer wall surface temperature measurements also provided experimental data to assess the capability of the CFD simulations in capturing the locally averaged flow and heat transfer characteristics throughout the diffuser flow path.

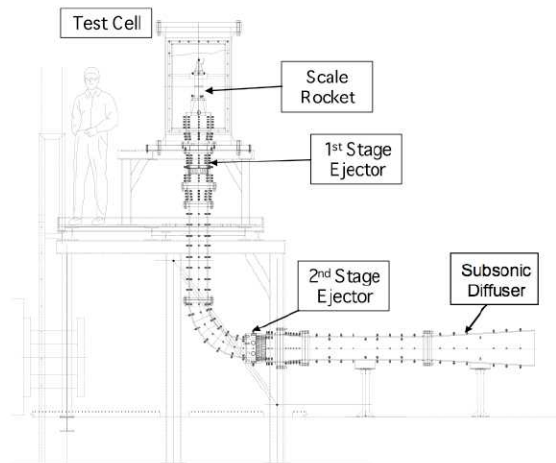


Figure 3: Subscale Altitude Test Facility

B. Acoustic Measurements and Data Collection

In order to anchor far-field acoustic models that were being using to estimate the A-3 test facility acoustic signature, a detailed acoustic mapping of the subscale test facility during its operation was performed. A radial arc of seven free-field microphones (B&K ½" Type 4191) were placed in what was preceived a priori to be the acoustic far-field of the subscale facility. Figure 4 shows that the seven microphones were placed at approximately 228 nozzle exit diameters away. Two additional microphones were placed at approximately half that distance on 45 and 90 degree nozzle aft directivity angles. The microphones had a reported accuracy of +/- 0.2dB for frequencies between 10 and 4000 Hz. The microphone data was sampled at a rate of 43kHz and then filtered using a bandpass, 3rd order, Butterworth filter with cutoff frequencies of 1Hz and 20kHz.

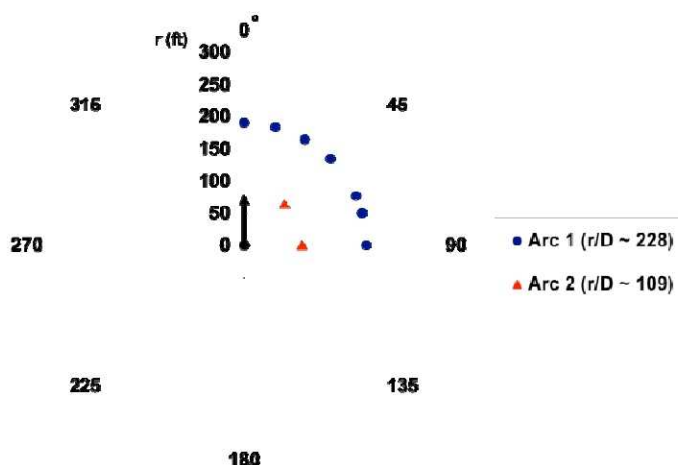


Figure 4: Placement of Microphone Sensors for Farfield Acoustic Mapping

IV. Results

A. Experimental Far-field Acoustic Data

The microphone data were processed using a lab-view based Fast Fourier Transform (FFT) acoustic code that was developed in-house and has been used previously on other NASA Stennis test programs. The lab-view code would provide time-averaged or transient one-octave, 1/3 octave or narrow-band spectra for each microphone. The results in this paper all show the one-octave averaged spectra over the 3 second rocket hot-fire test duration. The acoustic data acquired during steam ejector startup and shutdown have been removed from the time data in order to solely capture the nominal 100% power-level facility operation. Several acoustic tests were conducted for the 100% power-level condition which showed repeatability in the measurements to with ± 0.5 dB.

Figure 5 are the one-octave microphone spectra for the $r/D=228$ radial arc location. The data shows that the dominant acoustic levels are concentrated along a 45 degree angle with a peak frequency of 500 Hz at this radial location. The one exception is the microphone which is located directly downstream in the path of the plume. This microphone picked up a significant amount of low-frequency energy. One potential cause for this is the well known fact that low frequencies (or large-wavelengths) are not refracted as much because their wavelengths are much larger in comparison to the width of the shear layer. Also, Mach number and convection effects are more dominant on the low frequencies. Lastly, wind loading on the microphone could be possible since it is in the far but direct path of the steam laden plume.

One beneficial way to visualize these spectra is by normalizing the frequency based on the facility exit diameter and average exit velocity. In this case the average exit velocity was estimated from the CFD calculations. The resulting normalized spectra, given in Figure 6, indicated a preferred strouhal frequency of 0.1 to 0.2 at this radial location. Since this is a subscale system of A-3, we would expect the A-3 spectra to have a similar preferred Strouhal frequency range at this normalized radial location. It should be also noted that the preferred Strouhal frequency in the acoustic spectra is also a function of radial distance from the noise source. Figure 7 provides two 45 degree directivity spectra at different radial locations. The data show that as you move further away from the noise source the higher frequencies attenuate faster in the atmospheric environment resulting in the dominant frequency of the acoustic spectra shifting to lower values.

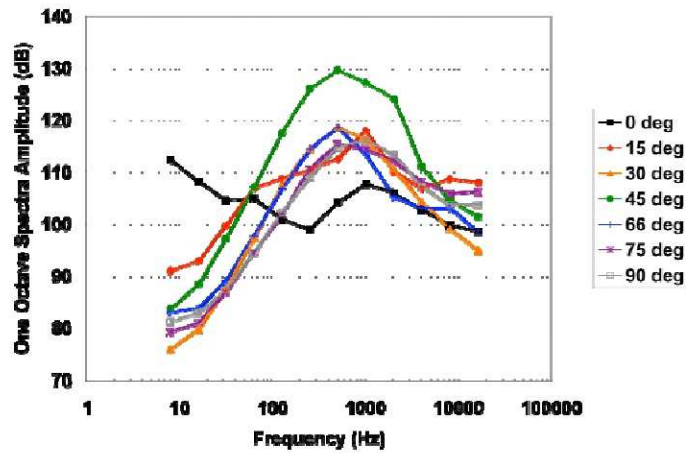


Figure 5: One-Octave Microphone Acoustic Spectra at $r/D=228$

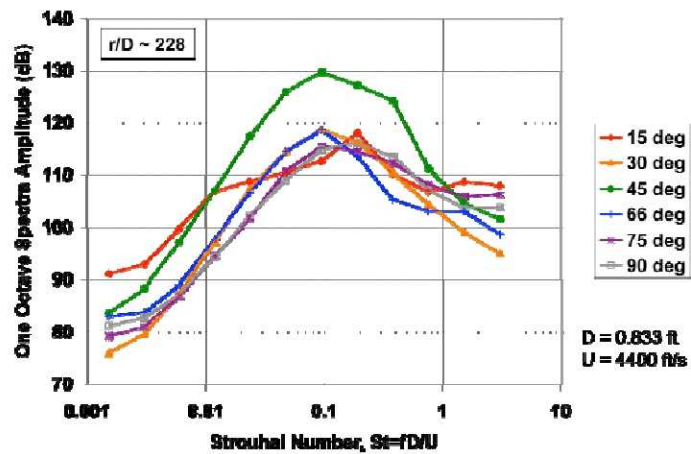


Figure 6: Normalized One-Octave Microphone Acoustic Spectra at $r/D=228$

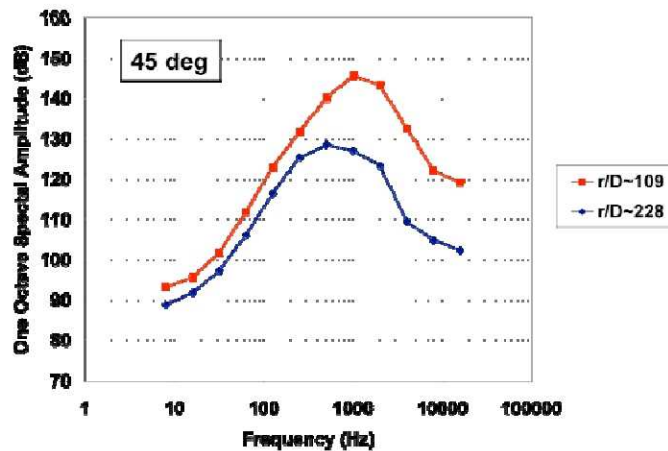


Figure 7: One-Octave Microphone Acoustic Spectra at 45 degree Directivity Angle (relative to the plume flow direction)

B. Assessment of the Acoustic Similarity Methodology

Fairly good qualitative agreement was obtained for the overall sound pressure level directivity using the acoustic similarity methodology as indicated by Figure 8. The symbols on the polar plot indicate experimental data and the line contours indicate model predictions. The only significant deviations between the model and data occurred at the high intensity lobe region of 45 degrees and for somewhat large directivity angles. Most of the OSPL directivity estimates were within ± 2 dB, which is within reason for this simplified scaling approach.

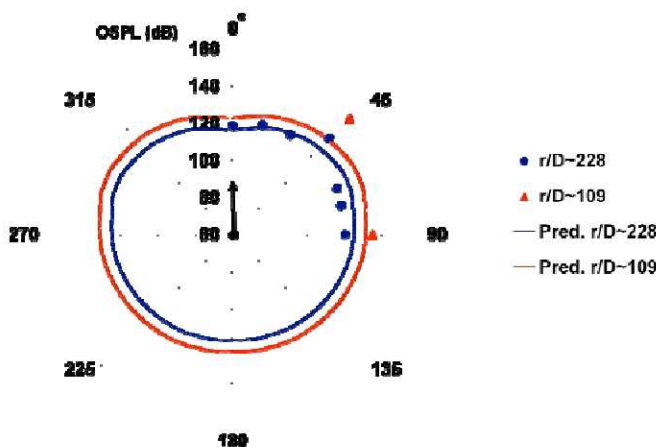
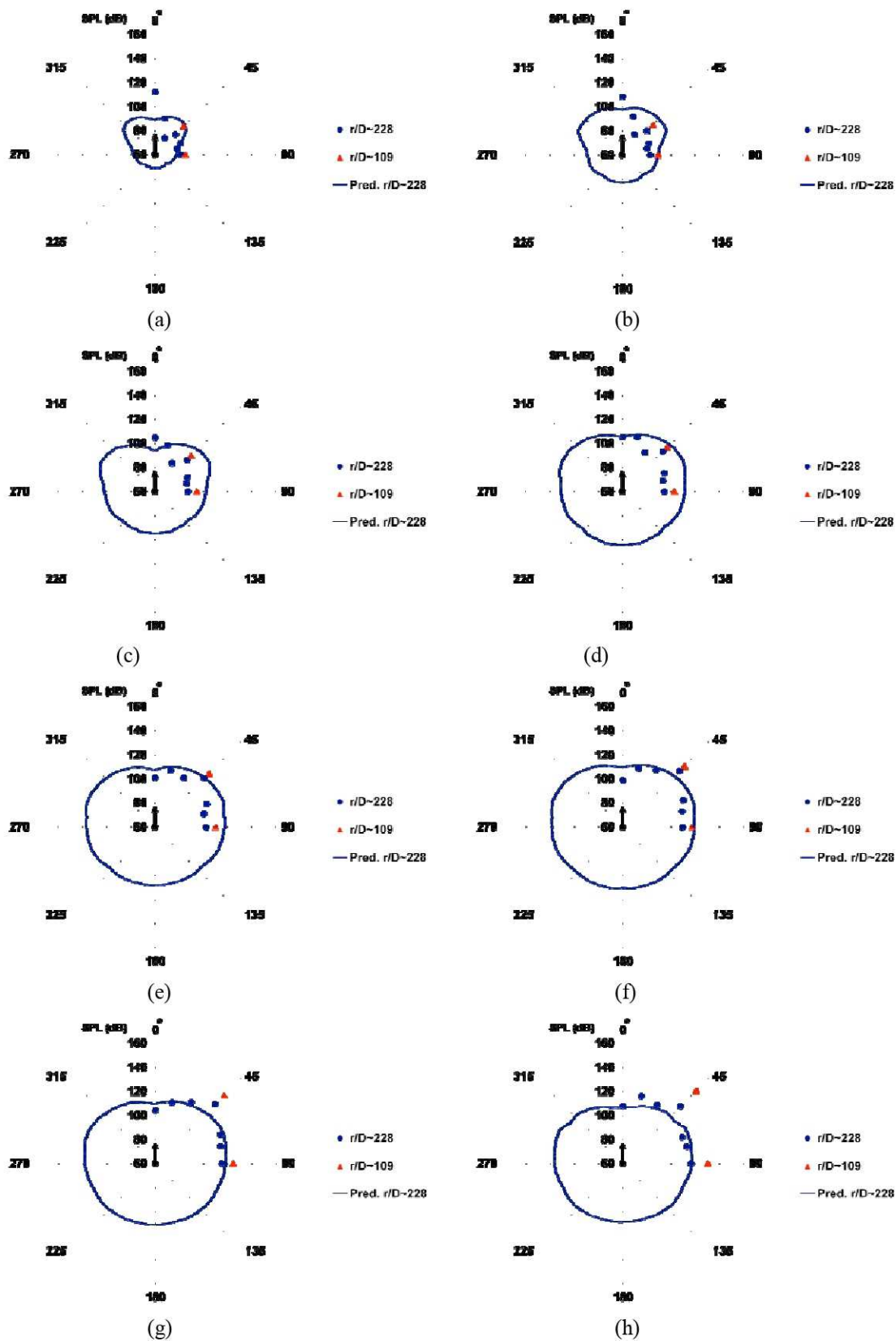


Figure 8: Comparison of OSPL Directivity Measurements and Acoustic Similarity Model Predictions at the Two Radial Arc Locations ($r/D=109$ and $r/D=228$).

Band-centered one-octave directivity polar plots are shown in Figure 9. The array of polar plots depict how the preferred directivity angle shifts with frequency. The data indicates that the low frequency (<60 Hz) or large-wavelengths of the jet noise are directed downstream with the plume. For larger wave lengths (60-2000Hz), the noise gets refracted to a preferential direction of approximately 45 degrees. This is dictated by the characteristics of the sub-scale plume. Once the frequency reaches above 2000 Hz, the acoustics nearly omni-directional with no preferential direction. *Further discussions and analyses of these results will be presented in the final manuscript.*



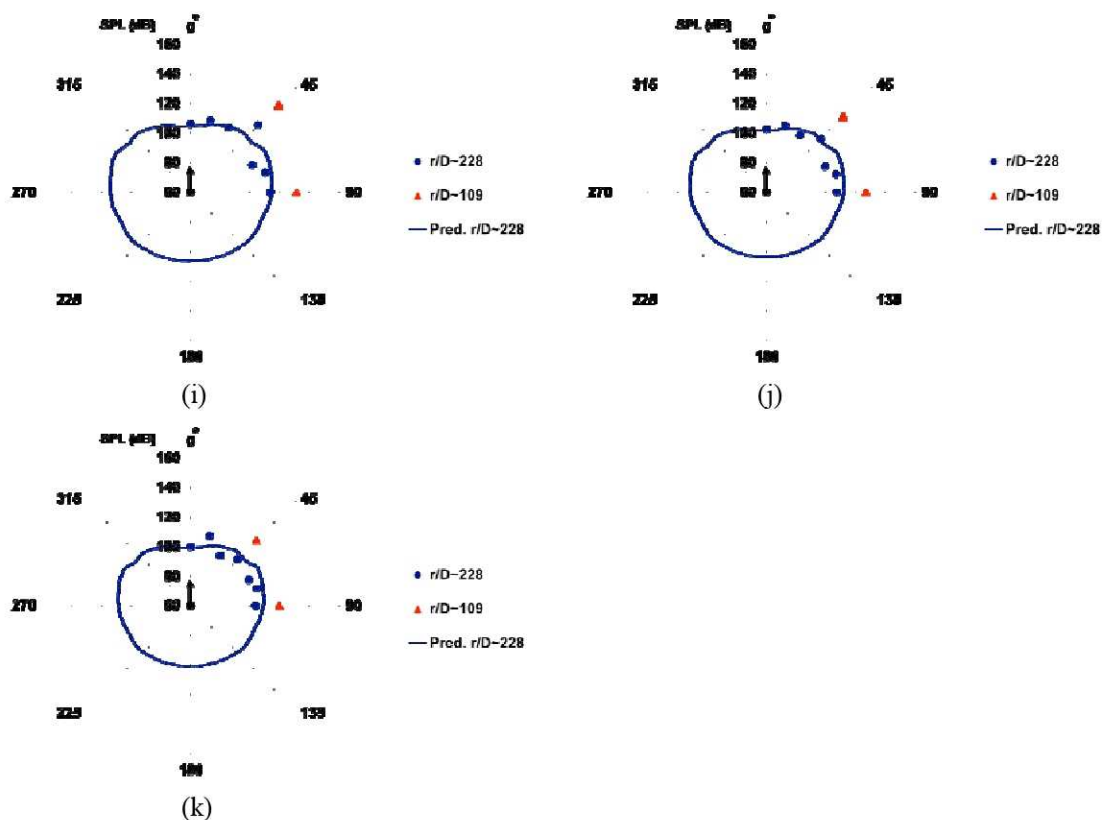


Figure 9: One-Octave Sound Pressure Level Directivities at One-Octave Band Centered Frequencies of (a) 8, (b) 16, (c) 31.5, (d) 63, (e) 125, (f) 250, (g) 500, (h) 1000, (i) 2000, (j) 4000, and (k) 8000 Hz.

C. Assessment of the CFD+Acoustic Analogy Methodology

Charts comparing the acoustic analogy methodology with that of the simplified acoustic similarity approach and the experimental microphone data will be added and discussed in the final manuscript. Some of the CFD plume simulations used to provide input to the acoustic analogy model have been depicted in Figure 10 below.

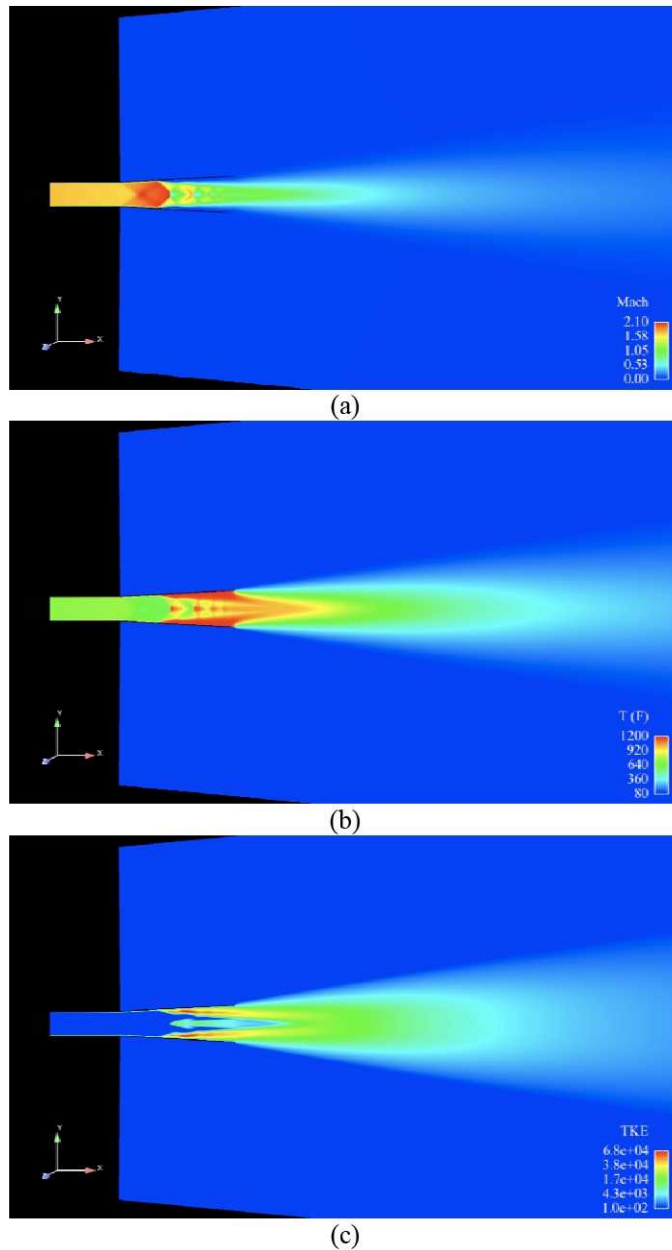


Figure 10: CFD Predicted Plume Conditions (a) Mach Number (b) Temperature and (c) TKE

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